Supplementary Material

1 Supplementary Material 1: Influence of climate change on marine predators - Ice dependent predators

Diversity of predator foraging strategies within sea ice

A diversity of foraging strategies exists in air-breathing predators to take advantage of the resources of the Antarctic sea ice zone despite its breathing constraint. Below is a non-exhaustive list of examples of behavior found within the Antarctic sea ice zone for seven polar predators: crabeater seals, minke whales, Weddell seals, southern elephant seals, emperor and Adélie penguins and snow petrels.

Crabeater seals in Marguerite Bay (Western Antarctic Peninsula) foraged in areas with higher than average but not complete sea ice cover likely to be associated with higher krill density, but still allowing an access to air to breath or ice to rest (Burns et al., 2004). They changed their distribution from open ocean in the vicinity of the shelf break in summer/autumn to the continental shelf in winter/spring.

Antarctic minke whales are the smallest baleen whale species yet the largest krill-dependent ice-affiliated endemic Antarctic predator. At broad spatial scales, minke whale distribution and density is most tightly coupled to the sea ice edge and areas in close proximity to this feature (Williams et al., 2014; Herr et al., 2019). During summer and into fall, individual minke whales have been shown to range broadly but maintain close proximity to the ice edge or are continuously in sea ice. However, in winter, while some minke whales are known to remain in Antarctic waters, some portion also migrate to subtropical areas for calving and breeding (e.g. Lee et al., 2017).

Among baleen whales, minke whales are likely able to subsist on lower densities of krill than other larger baleen whales that require dense krill patches to offset the energetic demands of their feeding style and large body size (Goldbogen et al., 2017). The diminutive body size of minke whales relative to other baleen whales also affords them the ability to navigate among tightly packed ice floes and find breathing opportunities that would be difficult for other species. Sea ice likely also helps minke whales avoid predation risk from killer whales. Thus, while the distribution of humpback whales is primarily driven by the distribution of krill, minke whale distribution is more dictated by a combination of proximity to sea ice and krill availability (Friedlaender et al., 2006). In sea ice environments minke whales have been shown to make extended excursions under ice to feed on shallow krill patches directly beneath sea ice that are unavailable to other baleen whales (Friedlaender et al., 2014). When they are found in sympatry with other baleen whales (e.g., humpback whales), minke whales associate with deeper prey patches that may not be as energetically efficient for larger whales to feed on (Friedlaender et al., 2009).

Weddell seals breathe through holes in year-round fast ice and with emperor penguins they are the only two warm-blooded predators using the Antarctic fast ice during winter (Burns and Kooyman, 2001). Weddell seals are ice-obligate species with the ability to break ice, and they require ice thick enough to haul out and thin enough to maintain breathing holes (Lake et al., 2005). They are known to interact with smaller features such as perennial tide cracks (Kooyman, 1981). For Weddell seals, the foraging activity is concentrated within 5km of a breathing hole, and they appear to move between holes as local food is depleted (Heerah et al., 2017).

Among **southern elephant seals**, about 50% of the males and 10% of the females travelled towards the Antarctic sea ice during their winter post-moulting trip to feed before returning to the Kerguelen colony. There, females follow the sea ice edge as it extends northward, while males remain on the continental shelf despite the increasing sea ice (Labrousse et al., 2017). Males spent on average 25 ± 20% (up to 75%) of their total trip time inside polynyas (Labrousse et al., 2018), whose unique biological and physical features make them winter oases for these marine predators: (i) open water access to breathe at the surface throughout the winter; (ii) concentrated biological activity with rich ecosystems that support large populations of mammals that are able to breathe and feed throughout the ice season (Arrigo and van Dijken, 2003; Karnovsky et al., 2007; Arrigo et al., 2015).

Emperor penguins forage under winter sea ice at two key periods and adopt different foraging strategies for each: after egg-laying, between autumn and mid-winter when females are rebuilding their reserves (while the males incubate eggs); and during the chick provisioning period from mid-winter to December when both males and females alternate periods of foraging. The tracking of adult emperor penguins in two different colonies in East Antarctica suggest the importance of less recognized small openings, including cracks, flaw leads and ephemeral short-term polynyas, as foraging habitats for emperor penguins (Labrousse et al., 2019). Those penguins spent 23% of their time in ephemeral polynyas and did not use the large/yearly persistent, well-studied polynyas, even if they occur much more regularly with predictable locations. From autumn to spring, emperor penguins in East Antarctica forage either in these open water areas near the continental slope, or in pack-ice regions further off-shore (Kirkwood and Robertson, 1997a; 1997b; Labrousse et al., 2019).

Adélie penguins forage within sea ice during the breeding season from October to January. They share a relationship with sea-ice cover in the foraging area similar to emperor penguins, this relationship tends to be quadratic (Ainley, 2002; Barbraud et al., 2015; Ballard et al., 2010; Le Guen et al., 2018). In years of low and high sea-ice cover, penguins modified their diving activity by diving deeper, diving more frequently and by resting for shorter periods of time at the surface between dives than in years with intermediate sea-ice cover (Le Guen et al., 2018). Intermediate sea ice cover tends to have positive effect on the distance from the colony to the open water (Ropert-Coudert et al., 2015), the visual performance of predators enhanced by increased light (Langbehn and Varpe, 2017), or the thermocline strength (Ballard et al., 2019) and on the prey availability with consequences on prey acquisition success and in turn breeding performance.

Snow petrels feed almost exclusively within the pack ice year-round on sea ice associated fishes (*Pleuragramma antarctica* and *Electrona antarctica*) and crustaceans (*Euphausia* spp) (Delord et al., 2016) by dipping and surface-seizing. They are also known to feed by ice-gleaning or pattering on the sides of icebergs (Marchant and Higgins, 1990). Snow petrels are associated with cold waters (≤ 1 °C) (Murphy, 1964) and only breed in the Antarctic zone. The species is often observed sitting on sea ice and icebergs (Ainley et al., 1993), they spent a large amount of time resting on the ice while moulting, a behaviour that cannot be distinguished from flight activity by the wet/dry activity recorders (Delord et al., 2016).

2 Supplementary Material 2: Interactions with commercial fisheries and resource extraction - Commercial exploitation throughout the Southern Ocean - past and present

Southern Ocean fisheries

Longlining - Commercial fisheries targeting Patagonian toothfish Dissostichus eleginoides have developed over the last 30 years and have now become the primary economic fishing activity in subantarctic waters. These fisheries currently all involve demersal longlining and operate on shelf edges (500 m – 2000 m deep) of South America and around the subantarctic islands and banks of the Southern Ocean (Collins et al., 2010). Stocks experienced substantial over-exploitation by IUU vessels during the 1990s and early 2000s (Agnew, 2000; Österblom and Sumaila, 2011), but are now highly regulated and monitored by a combination of national and international governance bodies, including CCAMLR. Commercial fisheries targeting Antarctic toothfish Dissostichus mawsoni in latitudes south of the Antarctic Convergence were initiated in the late 1990s in the Ross Sea region. These fisheries operate from December to May in waters managed solely by the CCAMLR as exploratory fisheries (Hanchet et al., 2015). Vessels use demersal longlines deployed at depths of 1000-2000 m. Most catches occur in the Ross Sea region (CCAMLR Subareas 88.1 and 88.2) but exploratory fishing also occurs in CCAMLR Areas 48 and 58.

Trawling - There are broadly two types of trawl fishing gear deployed in the Southern Ocean to target Antarctic krill and mackerel icefish. The fishery for Antarctic krill is primarily a coastal (on-shelf) pelagic midwater trawl that currently operates with either a traditional trawl which requires the net to be hauled back onto the vessel and its contents vented onto the deck, or a continuous vacuum pumping system where the net remains in the water but the catch is pumped from the cod end into holding tanks onboard the vessel and from there to the factory processing plant. Both trawling systems require nets fitted with marine predator entanglement mitigation measures being towed at slow speeds (~4knots). Mackerel icefish fisheries involve both midwater and demersal trawling and currently operate on shelves of South Georgia and Heard Island and McDonald Islands.

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